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Low-cost multimode diode-pumped Tm:YAG and Tm:LuAG lasers

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Abstract: We report a continuous-wave operation of Tm:YAG and Tm:LuAG lasers pumped with a low-cost, multimode AlGaAs laser diode. First, the lifetime and the absorbance behavior of 5 mm, 6% Tm^{3+}-doped YAG and LuAG crystals were thoroughly investigated. A low-cost multimode 3W laser diode at 781 nm was then used as a pump source for the Tm^{3+}-doped laser systems. Using three different output couplers, up to 636 mW of output power was obtained from Tm:YAG laser, with a slope efficiency of 29% at 2017 nm. The maximum output power was 637 mW in the Tm:LuAG laser, with a slope efficiency of 28% at 2023 nm. The lasing performances showed a decreasing slope efficiency with an increasing level of output coupling, which leads to a high upconversion. Furthermore, using a birefringent filter in the resonators, the laser outputs were tuned from 1942 to 2086 nm in the Tm:YAG resonator and from 1931 to 2107 nm in the Tm:LuAG case.

Key words: Lasers, diode-pumped lasers, solid-state lasers, Tm:YAG laser, Tm:LuAG laser, tunable lasers, infrared lasers

1. Introduction

Reduction in the complexity and cost of the solid-state laser systems has attracted growing interest in recent years. Especially in integrating large-scale production or other measurement systems; compact layouts, cost-effective techniques, and standardized fabrication present great advantages and improvements to laser systems and research in this field. One of the most efficient ways to accomplish these reductions is to use commercial multimode laser diodes as pump source in the laser systems, as they are one of the most promising methods of laser excitation. Recently, this approach was applied to Cr:LiCAF laser, using two commercially available AlGaAsP multimode laser diodes, and up to 880 mW output power was obtained at 800 nm [1].

Similar low-cost commercial diode-pumped solid-state lasers are needed in the 2 μm spectral region (due to operating in the eye-safe region) for a wide range of applications in medicine [2–6], remote sensing [7, 8], atmospheric communication [9, 10], spectroscopy [11], frequency metrology [11], and for pumping lasers and optical parametric oscillators at higher wavelengths [12–14]. One of the most common techniques to obtain laser light at 2 μm is a Tm^{3+}-ion based laser system. If a Tm^{3+}-ion doped crystal is excited at 780 nm ($\pm$15 nm depending on the host crystal), it emits a laser photon in the 2 μm band. Furthermore, pumping in the 780 nm band could lead to high cross-relaxation and upconversion effects, which can positively or negatively affect system performance [15, 16].

Typically, tunable Ti:sapphire lasers are used to excite Tm^{3+}-doped gain media [17–21]. Other pumping

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*Correspondence: ersen.beyatli@erdogan.edu.tr schemes include flash-lamp pumping [22, 23] and medium- or high-power diode pumping [15, 18, 19, 21, 24, 25]. However, these methods are, in general, bulky and costly. One of the best alternative is to use low-cost laser diodes in the pumping mechanism as in [1]. If the geometries of the resonator and pumping system are well aligned, laser operation can occur by pumping with the aforementioned diodes. This method has been applied to Tm:YAG lasers using two low-cost single-mode AlGaAs laser diodes [26]. However, the total output power in this work is restricted to 32 mW, because single-mode diodes only provide 200 mW input powers. A higher input power is needed to increase the output power.

This work demonstrates a commercial AlGaAs laser-diode-pumped Tm^{3+}-based systems. In the experiments, two Tm^{3+}-doped crystals, namely Tm:YAG and Tm:LuAG, were used for the gain media. The AlGaAs diodes provided 3W output power at 781 nm, which matched the Tm:YAG and Tm:LuAG crystals' absorption bands. The spectroscopic behavior of the crystals at 781 nm were investigated first. Then, after a stable laser resonator was constructed, their laser performance was measured. In the laser experiments, 636 and 637 mW output powers were obtained with Tm:YAG (at 2017 nm) and Tm:LuAG (at 2023 nm) lasers, respectively. These output powers are almost 20 times higher compared to those obtained in [26]. Furthermore, the laser outputs were tuned from 1942 to 2086 nm for the Tm:YAG laser and from 1931 to 2107 nm for the Tm:LuAG laser with a birefringent quartz filter. These tuning ranges are broader and smoother compared to that in [26] (which is 100 nm).

2. Experimental setup

To establish a compact and low-cost pumping system, a linearly polarized, multimode diode laser (RPMC LDX-3315-780) capable of producing up to 3W at a driving current of 3A was selected. The diode costs less than 250 USD (in high volume ordering), that corresponds to >12 mW per USD. Considering the previously mentioned low-cost experiment [26], the diode price in this experiment is likely to generate great interest in the relevant fields. The free-running wavelength of the diodes was 781 nm, which can be tuned to between 775 and 785 nm with a thermoelectric cooler. The diode was mounted on a standard C-mount. A commercial C-mount fixture (ILX LDM-4409) was used for housing the diode. The diode was controlled with a commercial diode driver (ILX LDX-5562) and a commercial temperature controller (ILX LDT-3353) (However, with a compact LD driver- and a TEC controller cards, this driving system could also be constructed in a more compact and cost-efficient manner). Considering our Tm^{3+} crystal absorption bands, we set the diode wavelength to 781 nm during the experiments (Figure. 1).

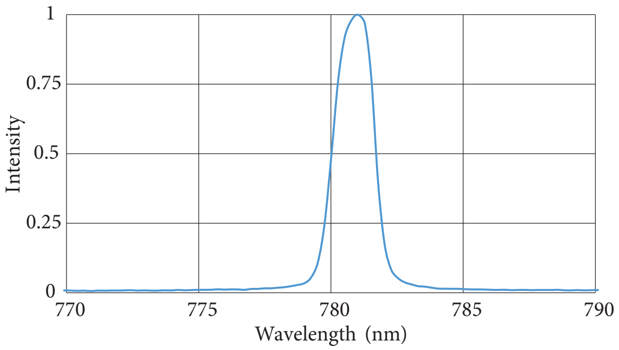

Figure 1. Free-operating spectrum of low-cost multimode laser diode.

To obtain stable laser operations, we used a four-mirror x-cavity geometry, as shown in Figure 2. A linearly polarized multimode diode laser (LD) was used to pump the Tm^{3+}-doped crystals through the input curved mirror (CM1). The pump beam was first collimated with an antireflection-coated aspheric lens (AL), with a focal length of 4.5 mm. Then, to minimize astigmatism, a cylindirical lens (CL) with 50 mm focal length was used to match the fast and slow axis divergence of the pump beam. The diode current was fixed to 3A during the experiments, as the beam alignment from the laser diode depends on the applied current. The input power was adjusted with a half-wave plate (HWP) and a polarizing beam splitter (PBS). An antireflection-coated input lens (ML) with a focal length of 50 mm was used to focus the pump beam inside the gain crystals. First, a knife-edge-based beam profiler (Thorlabs BP209-VIS) was employed to determine the waist of the pump beam in the absence of the gain medium. During this process, the collimating lens, the cylindirical lens and the input lens locations were carefully adjusted to obtain minimum waist lengths in the fast (198 μm) and the slow axes (128 μm). Following that, the crystals (6% Tm^{3+}-doped 5-mm Tm:YAG and 5-mm Tm:LuAG obtained from Scientific Materials) were placed at the focus point and the absrobance percentages of the crystals were measured at 781 nm. Furthermore, we modulated the pump light with a 20 Hz chopper and the modulated fluoresence light was collected and monitored in a 200 MHz oscilloscope (with a high speed InGaAs detector (Thorlabs PDA10D-EC)). From the average of 128 samples the crystal's $^3F_4$ state lifetimes were estimated.

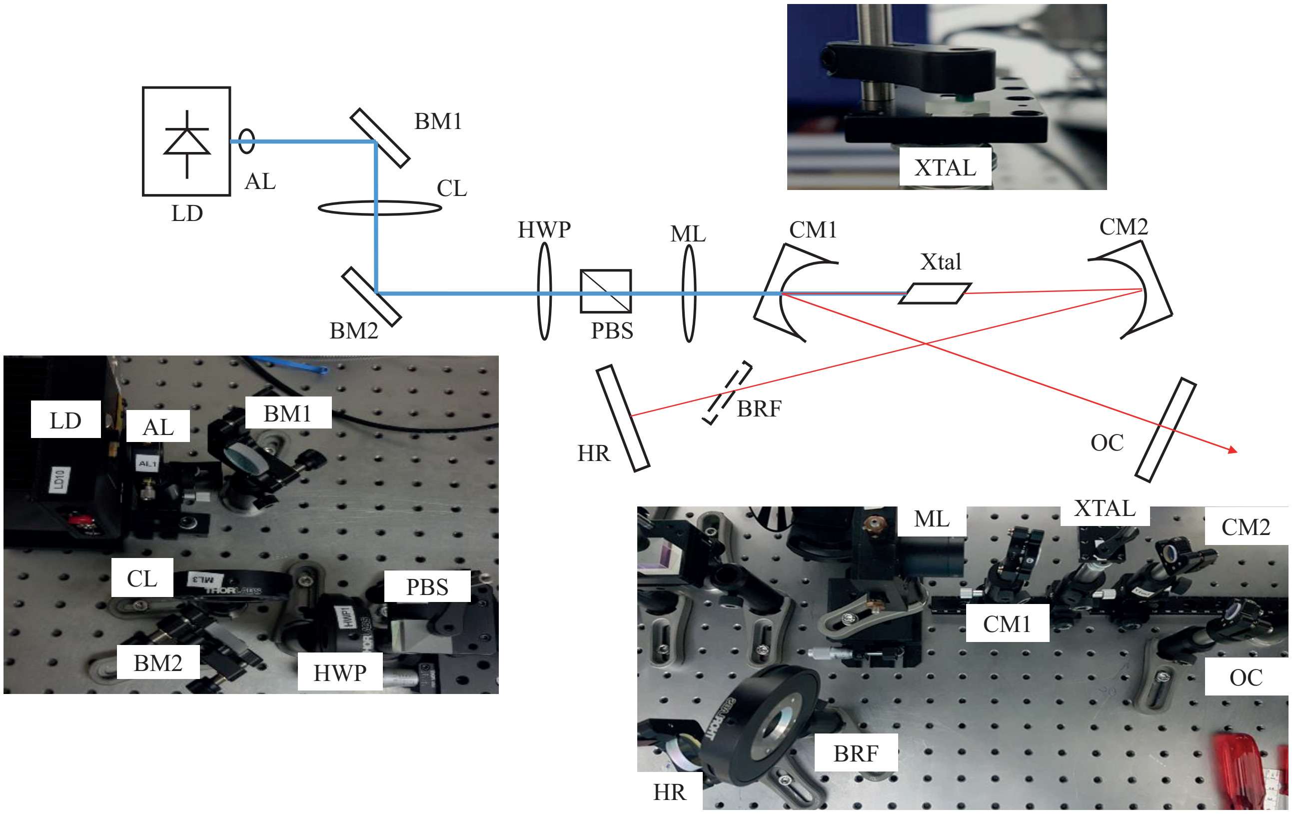

Figure 2. Low-cost multimode laser-diode-pumped Tm:YAG and Tm:LuAG setup.

The laser resonator consisted of two intracavity input curved mirrors (CM1 with R = 50 mm and CM2 with R=75mm), a highly reflective end mirror (HR) and a wedged output coupler (OC). In the first part of the laser experiments, the gain medium, which was a 5 mm, uncoated Brewster-Brewster-cut, 6% Tm^{3+}-ion doped YAG crystal, was positioned at a Brewster incidence between CM1 and CM2. To obtain maximum output power, the HR and OC arm lengths were set to 11 and 28.5 cm, respectively. The entire layout was setup on a 30 cm × 60 cm table (excluding the diode drivers; if space is of concern, those can be replaced with compact electronic cards). In this configuration, three different output coupling levels (i.e. 1.33%, 2.7%, and 4.75%) were used in the resonators. Then, a 3-mm quartz birefringent filter (BRF) with an optical axis of 45 degree to the surface of the plate was used in the HR arm to tune the laser wavelength (with an APE Berlin Ext. IR Spectrometer) [27]. Next, the gain medium was replaced with a 5-mm, uncoated Brewster-Brewster-cut Tm:LuAG crystal with, again a 6% Tm^{3+} ion doping level. Keeping the same arm lengths as in the previous crystal, the same measurements were repeated.

3. Results and discussions

In the spectroscopic experiments, for the 5-mm Tm:YAG crystal, the absorbance percentage was measured to be 85%, and the exponential fit to a $^3F_4$ state lifetime data resulted in 15 ms fluorescence lifetime. The 5-mm Tm:LuAG crystal absorbed 82% of 781 nm light and the $^3F_4$ state lifetime was estimated to be at 16 ms (Figure 3).

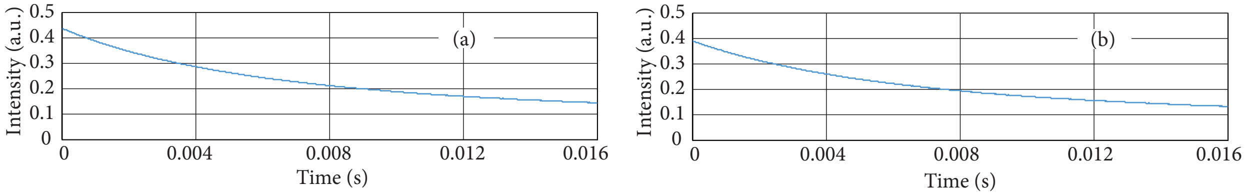

Figure 3. Measured variation of fluorescence lifetime of (a) Tm:YAG, (b) Tm:LuAG crystal with respect to time.

In the 5-mm Tm:YAG laser experiments, a maximum of 636 mW output power was obtained with the 1.33% output coupler (Figure 4). For the other output couplers, the maximum obtained output powers were 560 mW for the 2.7% output coupler and 423 mW for the 4.75% output coupler. The slope efficiencies were 29% for the 1.33% output coupler; 27% for the 2.7% output coupler and 22% for the 4.75% output coupler. The estimated threshold values (obtained by line fitting) were 398 mW, 500 mW, and 688 mW for the 1.33%, 2.7%, and 4.75% output couplers, respectively. From the threshold values, one can estimate the round-trip cavity loss (crystal loss + resonator loss) with the formula $Pth = A(T + L)$, where Pth is the threshold power, A is the proportionality constant, T is the transmission of the output coupler and L is the round-trip cavity loss [26, 32]. According to these threshold values the cavity loss was estimated to be 3.27% (Figure 5). Each mirror used in the resonator has a loss of 0.1% (five mirror bouncing in one round-trip); hence, the round-trip Tm:YAG crystal loss could be estimated to be 2.77%. The free operating wavelength of the laser output was 2017 nm (Figure 6). By inserting the birefringent tuning filter into the system where the maximum output power was obtained (i.e. 636 mW with the 1.33% output coupler), the output wavelength was tuned from 1942 nm to 2086 nm (Figure 7).

In the 5-mm Tm:LuAG laser system, the maximum output power was 637 mW (Figure 8), obtained with the 1.33% output coupler. The estimated threshold pump power was 329 mW and the slope efficiency was 28%. For the 2.7% output coupling level, the maximum output power was 563 mW with 26% of slope efficiency. The estimated threshold value in this case was 500 mW. In the 4.75% output coupling case, as high as 423 mW

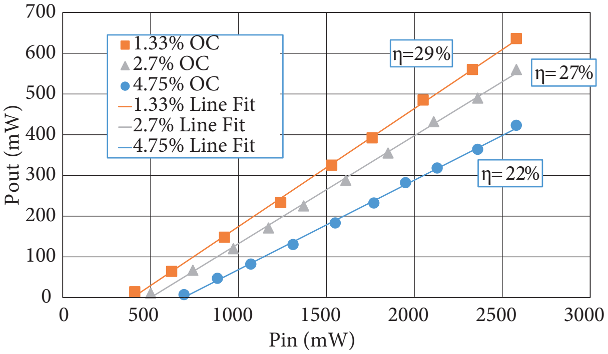

Figure 4. Measured power efficiencies of the Tm:YAG laser pumped with a low-cost multimode 3W AlGaAs laser diode (η indicates the slope of the closest line).

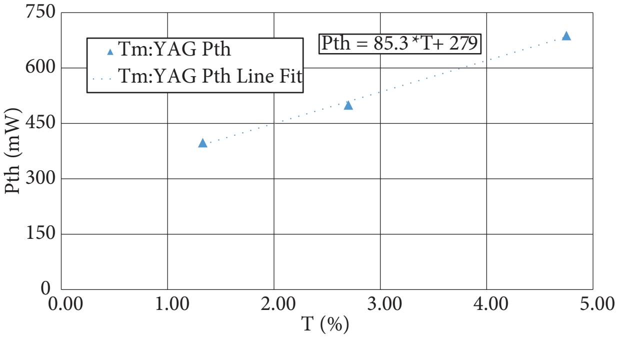

Figure 5. Measured and line-fit variation of the incident threshold pump power (Pth) as a function of the output coupler transmission (T) for the Tm:YAG laser.

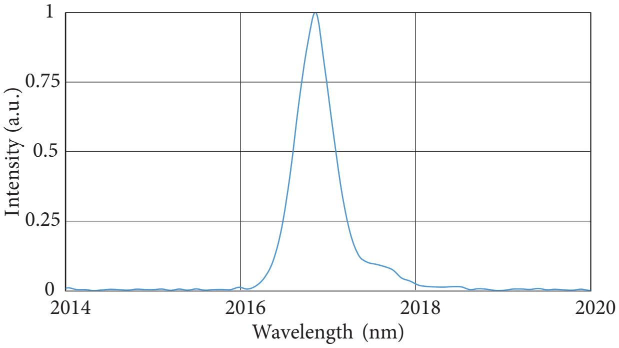

Figure 6. Free operating wavelength of the Tm:YAG laser output.

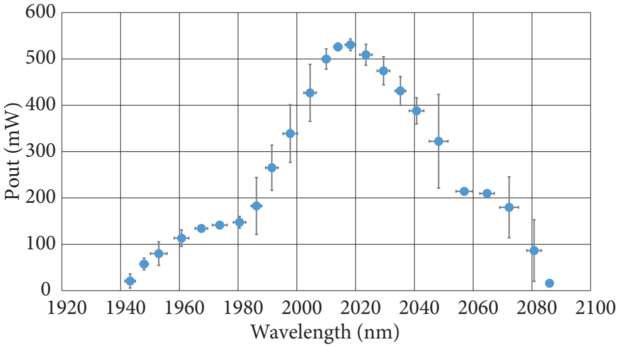

Figure 7. Measured tuning curve of Tm:YAG laser pumped with 3W laser diode with 1.33% OC. A 3-mm quartz birefringent filter was used for tuning.

of output power was obtained, with 24% power efficiency. The estimated threshold value was 600 mW in this case. From these threshold values the cavity loss was estimated to be 3.26% (Figure 9). Considering the mirror losses, the round-trip Tm:LuAG crystal loss was estimated to be 2.76%. The free operating wavelength of this system was 2023 nm (Figure 10), and by inserting the birefringent tuning plate into the system, the output could be tuned from 1931 to 2107 nm (Figure 11).

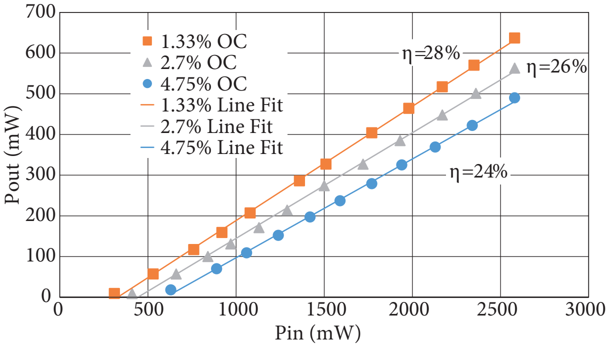

Figure 8. Measured power efficiencies of the Tm:LuAG laser pumped with a low-cost multimode 3W AlGaAs laser diode (η indicates the slope of the closest line).

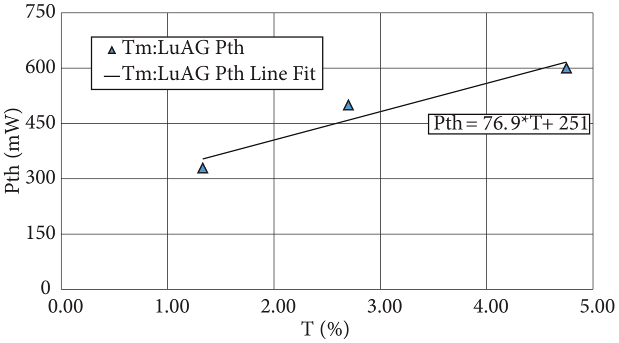

Figure 9. Measured and line-fit variation of the incident threshold pump power (Pth) as a function of the output coupler transmission (T) for the Tm:LuAG laser.

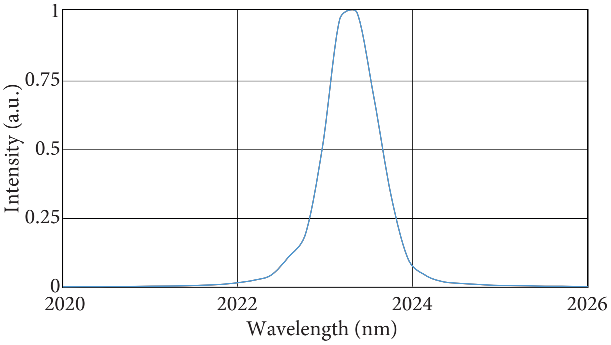

Figure 10. Free operating wavelength of the Tm:LuAG laser output.

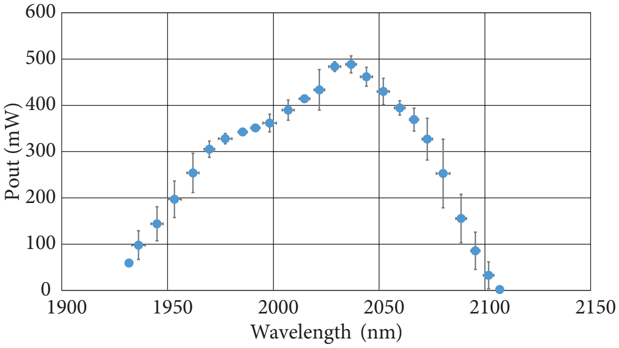

Figure 11. Measured tuning curve of Tm:LuAG laser pumped with 3W laser diode with 1.33% OC. A 3-mm quartz birefringent filter was used for tuning.

Comparing these results, it was first observed that in both crystals the slope efficiencies were higher at the lower output coupling level. This effect, more clearly observed in the Tm:YAG laser (i.e. increasing the output coupling level from 1.33% to 4.75% yielded a decrease in the slope efficiency from 29% to 22%). This finding contradicts Caird's theory, which states that an increase in output coupling level leads to an increase in slope efficiency [28]. This contradiction was previously observed in different Tm^{3+}-doped laser systems [29–31], mainly due to an upconversion process in Tm^{3+}-ions [15, 16]. Second, in all cases, decreasing the output coupling level yielded lower threshold values, which is in good agreement with the classical laser theory [32]. These two findings (higher slope efficiency and lower threshold value at the lowest output coupling level) results in that the highest output power was attained with the lowest level of output coupling level. Furthermore, in the current experiments, it was observed that the Tm:LuAG laser had a longer and smoother tuning range performance than the Tm:YAG laser. This finding contradicts previous experiments [9, 30] possibly due to a higher Tm^{3+} ion concentration in the current experiments (i.e. 6%) compared to the previous works (i.e. 4%).

4. Conclusions

These experiments demonstrated that a low-cost 3W multimode AlGaAs laser diode at 781 nm is a suitable pump source for the Tm:YAG and Tm:LuAG lasers. Using these diodes, more than 630 mW output power was obtained in the 2 μm regime. Furthermore, using a birefringent filter, the output wavelength was tuned over 175 nm in this 2 μm regime. As these diodes cost only 250 USD and could be driven with low-cost electronic cards, this method may be of high interest for applications involving pumping Tm^{3+} laser systems, the diode system and the resonator in a compact layout, which may make these laser systems more desirable, especially in medical and atmospheric communication areas.

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References

[1] Demirbas U, Sennaroglu A, Kärtner FX, Fujimoto JG. Comparative investigation of diode pumping for continuous-wave and mode-locked Cr^{3+}:LiCAF lasers. Journal of the Optical Society of America B 2009; 26 (1): 64-79. doi: 10.1364/JOSAB.26.000064

[2] Wolters M, Kramer MW, Becker JU, Christgen M, Nagele U et al. Tm:YAG laser en bloc mucosectomy for accurate staging of primary bladder cancer: early experience. World Journal of Urology 2011; 29 (4): 429-432. doi: 10.1007/s00345-011-0686-z

[3] Musi G, Russo A, Conti A, Mistretta FA, Trapani ED et al. Thulium–yttrium–aluminium–garnet (Tm:YAG) laser treatment of penile cancer: oncological results, functional outcomes, and quality of life. World Journal of Urology 2018; 36 (2): 265-270. doi: 10.1007/s00345-017-2144-z

[4] Kallidonis P, Kamal W, Panagopoulos V, Vasilas M, Amanatides L et al. Thulium laser in the upper urinary tract: does the heat generation in the irrigation fluid pose a risk? evidence from an in vivo experimental study. Journal of Endourology 2016; 30 (5): 555-559. doi: 10.1089/end.2015.0768

[5] Scott NJ, Cilip CM, Fried NM. Thulium fiber Laser ablation of urinary stones through small-core optical fibers. IEEE Journal of Selected Topics in Quantum Electronics 2009; 15 (2): 435-440.doi: 10.1109/JSTQE.2008.2012133

[6] Netsch C, Bach T, Herrmann TRW, Gross AJ. Update on the current evidence for Tm:YAG vapoenucleation of the prostate 2014. World Journal of Urology 2015; 33 (4): 517-524. doi:10.1007/s00345-014-1417-z

[7] Targ R, Steakley BC, Hawley JG, Ames LL, Forney P et al. Coherent lidar airborne wind sensor II: flight-test results at 2 and 10μm. Applied Optics 1996; 35 (36): 7117-7127. doi: 10.1364/AO.35.007117

[8] Yu J, Petros M, Singh UN, Refaat TF, Reithmaier K et al. An airborne 2-μm double-pulsed direct-detection lidar instrument for atmospheric CO_2 column measurements. Journal of Atmospheric and Oceanic Technology 2016; 34 (2): 385-400. doi: 10.1175/JTECH-D-16-0112.1

[9] Kmetec JD, Kubo TS, Kane TJ, Grund CJ. Laser performance of diode-pumped thulium-doped Y3Al5O12, (Y, Lu)3Al5O12, and Lu3Al5O12 crystals. Optics Letters 1994; 19 (3): 186-188. doi: 10.1364/OL.19.000186

[10] Kaushal H, Kaddoum G. Optical communication in space: challenges and mitigation techniques. IEEE Communications Surveys and Tutorials 2017; 19 (1): 57-96. doi: 10.1109/COMST.2016.2603518

[11] Galzerano G, Svelto C, Bava E. Diode-pumped 2μm optical oscillator for high-resolution spectroscopy and frequency metrology. IEEE Transactions on Instrumentation and Measurement 2001; 50 (4): 1003-1006. doi: 10.1109/19.948315

[12] Budni PA, Pomeranz LA, Lemons ML, Miller CA, Mosto JR et al. Efficient mid-infrared laser using 1.9-μ-pumped Ho:YAG and $ZnGeP_2$ optical parametric oscillators. Journal of the Optical Society of America B 2000; 17 (5): 723-728. doi: 10.1364/JOSAB.17.000723

[13] Nabors CD, Ochoa J, Fan TY, Sanchez A, Choi HK et al. Ho:YAG laser pumped by 1.9-μm diode lasers. IEEE Journal of Quantum Electronics 1995; 31 (9): 1603-1605. doi: 10.1109/3.406370

[14] Budni PA, Lemons ML, Mosto JR, Chicklis EP. High-power/high-brightness diode-pumped 1.9-μm thulium and resonantly pumped 2.1-μm holmium lasers. IEEE Journal of Selected Topics in Quantum Electronics 2000; 6 (4): 629-635. doi: 10.1109/2944.883377

[15] Lai KS, Phua PB, Wu RF, Lim YL, Lau E et al. 120-W continuous-wave diode-pumped Tm:YAG laser. Optics Letters 2000; 25 (21): 1591-1593. doi: 10.1364/OL.25.001591

[16] Rustad G, Stenersen K. Modeling of laser-pumped Tm and Ho lasers accounting for upconversion and ground-state depletion. IEEE Journal of Quantum Electronics 1996; 32 (9): 1645-1655. doi: 10.1109/3.535370

[17] Stoneman RC, Esterowitz L. Efficient, broadly tunable, laser-pumped Tm:YAG and Tm:YSGG cw lasers. Optics Letters 1990; 15 (9): 486-488. doi: 10.1364/OL.15.000486.

[18] Bourdet GL, Muller RA. Tm,Ho:YLF microchip laser under Ti:sapphire and diode pumping. Applied Physics B 2000; 70 (3): 345-349. doi: 10.1007/s003400050055

[19] Mateos X, Petrov V, Liu J, Pujol MC, Griebner U et al. Efficient 2-μm continuous-wave laser oscillation of Tm^{3+}: $KLu(WO_4)_2$. IEEE Journal of Quantum Electronics 2006; 42 (10): 1008-1015. doi: 10.1109/JQE.2006.881629

[20] Trapani FD, Mateos X, Petrov V, Agnesi A, Griebner U et al. Continuous-wave laser performance of Tm:$LuVO_4$ under Ti:sapphire laser pumping. Laser Physics 2014; 24 (3): 035806-035806. doi: 10.1088/1054-660X/24/3/035806

[21] Mateos X, Trapani FD, Aguiló M, Díaz F, Griebner U et al. Diode-pumped continuous-wave (Ho,Tm):$KLu(WO_4)_2$ laser with >1 W output power. Optical Materials Express 2014; 4 (11): 2274-2279. doi: 10.1364/OME.4.002274

[22] Barnes NP, Murray KE, Jani MG, Hutcheson RL. Flashlamp-pumped-room-temperature Ho:Tm:LuAG laser. In: Photonics West '95; San Jose, CA, USA; 1995. pp. 2374-2379.

[23] Tsai TY, Birnbaum M. Q-switched 2-μm lasers by use of a Cr^{2+}:ZnSe saturable absorber. Applied Optics 2001; 40 (36): 6633-6637. doi: 10.1364/AO.40.006633

[24] Zhu H, Zhang Y, Zhang J, Zhang Y, Duan Y et al. 1.96-μm Tm:YAG ceramic laser. IEEE Photonics Journal 2017; 9 (6): 1-7. doi: 10.1109/JPHOT.2017.2766026

[25] Yumoto M, Saito N, Urata Y, Wada S. 128 mJ/pulse, laser-diode-pumped, Q-switched Tm:YAG laser. IEEE Journal of Selected Topics in Quantum Electronics 2015; 21 (1): 364-368. doi: 10.1109/JSTQE.2014.2338872.

[26] Beyatli E, Naghizadeh S, Kurt A, Sennaroglu A. Low-cost low-threshold diode end-pumped Tm:YAG laser at 2.016 μm. Applied Physics B 2012; 109 (2): 221-225. doi: 10.1007/s00340-012-5188-1

[27] Demirbas U. Off-surface optic axis birefringent filters for smooth tuning of broadband lasers. Applied Optics 2017; 56 (28): 7815-7825. doi: 10.1364/AO.56.007815

[28] Cairo JA, Deshazer LG, Nella J. Characteristics of room-temperature 2.3-μm laser emission from Tm^{3+} in YAG and $YAIO_3$. IEEE Journal of Quantum Electronics 1975; 11 (11): 874-881. doi: 10.1109/JQE.1975.1068541

[29] Yorulmaz I, Sennaroglu A. Low-threshold diode-pumped 2.3-μm Tm^{3+}:YLF lasers. IEEE Journal of Selected Topics in Quantum Electronics 2018; 24 (5): 1-7. doi: 10.1109/JSTQE.2018.2791409

[30] Li YF, Wang YZ, Ju YL. Comparative study of LD-pumped Tm:YAG and Tim:LuAG lasers. Laser Physics 2008; 18 (6): 722-724. doi: 10.1134/S1054660X08060042

[31] Li YF, Yao BQ, Liu YM, Wang YZ, Ju YL. Widely tunable cw diode-pumped 1.9-μm Tm:$GdVO_4$ laser at room temperature. Chinese Physics Letters 2007; 24 (3): 724-726. doi: 10.1088/0256-307X/24/3/037

[32] Sennaroglu A. Photonics and Laser Engineering: Principles, Devices, and Applications. 1st ed. Chicago, IL, USA: McGrew Hill, 2010.